Biogeochemistry of Exploration Analogs

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Overview: Understanding the origins, distribution, and nature of life in the universe is a core scientific element in the vision for space exploration, and is among the most fundamental quests undertaken by mankind. A functional search for life in the universe must be built on a broad understanding of the coupled evolution of geological, chemical, and biological processes within a host planet or solar system. The conjunction of these processes provides the context for habitability, the origins of life, and the production of biosignatures that may ultimately lead to detection of extraterrestrial life. We advocate an integrative, interdisciplinary R&A program to study these biogeochemical processes, particularly in ecosystems representing analogs of potential exploration and search-for-life targets. Substantive progress in a broad-based biogeochemistry initiative would support a variety of scientific elements that enable the exploration vision. More specifically, the research areas that form the focus of this document will lead directly to enhanced understanding and definition of *biosignatures*, with clear support of both Solar System and extrasolar exploration missions.

Key Features of a Biogeochemistry Initiative: Biogeochemistry comprises the study of life's role in mediating planetary chemistry. The terrestrial example tells us that life's impacts may constitute the dominating force in chemical cycling at a planet's surface, and can be substantial and observable at a global scale. It is this altered planetary chemistry – specifically, the formation of uniquely biogenic chemical signatures – that constitutes the chief evidence on which we will base a search for extraterrestrial life within and beyond our solar system. Similarly, learning how the biogeochemical cycles work on Earth is a crucial step towards optimizing potential human interactions with the (bio?)geochemical processes and reservoirs on other planets. To effectively inform and drive exploration, a comprehensive initiative in biogeochemistry should:

(a) Seek to understand geochemical cycling on both inhabited and lifeless worlds – biogeochemistry and "abiogeochemistry". These constitute "signal" and "noise", respectively, in the chemical signatures that will be used to detect life on other worlds. With particular reference to "abiogeochemistry", it is critical to understand (i) the constraints imposed on would-be biological activity by resource cycling within the planetary matrix (e.g., material and energy fluxes resulting from tectonism, surface-subsurface exchange processes, weathering, stellar irradiance and associated photochemistry), and (ii) the formation of potential "false positive" biosignatures as a result of geochemical processes or delivery of exogenous materials.

(b) Begin with a focus on terrestrial ecosystems, and continually seek to generalize results into the broader reference frame of solar and extrasolar exploration. Studies of terrestrial systems that serve as analogs of prospective exploration targets will be particularly effective in this regard. Appropriate analogs include both temporal analogs (i.e., characteristic stages in planetary biogeochemical evolution) and ecotype analogs (i.e., specific geological settings or specific biological "lifestyles"). Appropriate temporal analogs may reference earlier stages in Earth history, corresponding to significantly different planetary oxidation state (e.g., oxygen-free atmosphere; sulfate-free, iron- or sulfide-rich oceans, etc.) or solar irradiance characteristics. These may be targeted by selecting existing suitable ecosystems, or by "creating" suitable environments through physicochemical manipulation of existing systems. Appropriate ecotype analogs may include specific geologic settings relevant to Mars or Europan exploration (e.g., evaporitic or sedimentary environments, and sub-ice environments, respectively) or metabolic lifestyles relevant to specific exploration targets (e.g., a focus on photosynthetic systems in reference to exoplanet, TPF-type searches, or a focus on chemosynthetic, subsurface life in reference to solar system exploration).

(c) Integrate studies on scales ranging from microscopic to planetary. Ultimately, the biological contribution to planetary chemistry is generated, and must first be understood, at the level of individual organisms. Indeed, the opportunity for detailed physical sampling within our own solar system may allow us to seek evidence of life at the microscopic or local scale. Yet, particularly in the telescopic search for life on extrasolar worlds, life detection may also depend critically on understanding biogeochemistry at the planetary scale. In addition to studies that target a spectrum of scales, it is also critical to include elements and techniques capable of integrating the results of such studies into a single, coherent picture of global biogeochemistry. The chief tools of integration will be both conceptual models and, increasingly, numerical simulations (e.g. "systems of systems") capable of coupling organismal, local, regional, and global scale processes.

(d) Combine existing and developing strengths in key scientific disciplines towards problems in biogeochemistry and, critically, towards issues of specific relevance to NASA's exploration goals. In a real-world context, the processes of biology, geology, and chemistry are inseparably intertwined. The most significant advances in understanding biogeochemical processes will therefore likely occur when the tools of a variety of disciplines are brought to bear in the study of a single system. On the local ecosystem scale, it is critical to integrate the inputs of microbial ecology, geochemistry, microbiology, and molecular biology. On a global scale, the results of local-scale studies must be integrated with atmospheric chemistry, oceanography, and geology (e.g., tectonism and related mantle-crust-surface exchange processes). Using organic and geochemical biomarkers to probe Earth's deep history, we can also integrate studies of biogeochemical cycling in modern systems with a record of biogeochemical evolution over geologic time scales. With an integrated, global-scale understanding of biogeochemistry, the Earth *as a whole* presents an analog for remote life detection studies. We can capture this analog and inform the telescopic search for extrasolar life by developing new Earth-orbiting and ground-based observation platforms that fine tune the process of biosignature detection in the terrestrial model system. A continual necessity in these efforts is to harness the considerable existing expertise and research in terrestrial biogeosciences towards problems and systems of specific relevance to solar and extrasolar exploration. This can be functionally accomplished by (i) R&A efforts that engage the broader academic community in focused research on exploration analog systems, and (ii) perhaps most directly, by personnel who are both active in the terrestrial biogeosciences community *and* fully engaged in NASA missions and exploration goals.

Relevance to Exploration Science: We advocate an integrative R&A program that seeks to understand the biogeochemistry of exploration analogs. The most direct impact of such a program would be a greatly enhanced understanding of the processes leading to *biosignature* formation, and formation of potential "false positive" signatures. A broad understanding of biosignatures lies at the very core of any effort to seek extraterrestrial life. A program that seeks an integrated understanding of biogeochemistry on local to planetary scales will thus be highly relevant to exploration missions for both solar system and extrasolar targets.